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Engineering Report ER-TC-SER 82-3

Overview of Ricochet Effects on Safety Impact Areas

23 April 1982

Prepared for:
Armament Division (AD)

Directorate of Range Safety (SER)

Contract No. F08635-79-C-0140
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FOREWORD

The work in this report was sponsored by the Directorate of Range Safety (SER) under Contract No. F08635-79-C-0140, and is a deliverable item under Study Task Order SER 82-3. The work was monitored by Mr. Walter Monteith and Mr. Robert H. Thompson.

ABSTRACT

An overview of ricochet effects on the safety control of impact areas during advanced tactical weapon tests on the Eglin ranges is presented. Archived film and data related to ricochet are reviewed, and a methodology capable of generating adequate safety criteria for tests which have a high probability of ricochet is proposed. The proposed methodology will make use of existing range planning methodology and computer codes in developing the ricochet safety criteria.

1.0 INTRODUCTION

AD weapon tests which involve shallow impact angles often result in ricochet. In order to control the safety of personnel and aircraft during such tests, it is essential to know the extent of the space hazarded by the ricocheting weapons and fragments. Impact hazard zones, safe personnel separation distances and safe aircraft altitudes have been developed for some weapons (e.g., GP bombs, 2.75" rockets, 20 mm and 30 mm rounds). However, the developed safety criteria have often been based upon tenuous physical assumptions and have, in some cases, been made unnecessarily stringent due to a lack of hard data and due to a desire to be conservative for safety reasons. In addition, ricochet safety control for several current and planned weapons (e.g., Maverick, GBU-15, LLLGB, WASP, Hyper-velocity Missile) has been subject to little or no analysis, although it is known that film and data which might be of value in analyzing ricochet hazards related to some of these weapons exists within the archives of AD and other agencies.

An overview and analysis of ricochet effects on the safety control of impact areas during advanced tactical weapons tests on the Eglin ranges is needed in order to ensure that the criteria for safety control are reasonable and adequate on tests involving a high probability of ricochet and that the criteria are not unnecessarily test restrictive. To accomplish this objective, the following tasks were performed during this study:

1) Films and data existing in AD and other archives relating to the ricochet of weapons to be tested by AD were reviewed.
2) Current AD range safety ricochet hazard criteria and methodologies available for the development of these criteria were reviewed.
3) Deficiencies in the current criteria and methodologies were identified.
4) A plan for improving the existing AD ricochet hazard criteria and methodologies was developed.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

The following conclusions resulted from this study:

1) The current AD ricochet criteria are poorly defined. The ricochet criteria of guns and rockets are based on maximum energy ricochet performance, and are very conservative in identifying a potential ricochet impact area. Ricochet criteria for bombs are based mainly on the combined historical experience of various range safety officers with bomb ricochet. The usual approach is to add an additional buffer zone to the initial impact area requirements (6000 feet for MK-82/MK-84 inert warheads) to account for potential ricochet.

2) A review conducted during this study of archived films of ricochets occurring during advanced weapon tests (e.g., GBU-15, LGB, LLLGB, MAVERICK) suggests strongly that ricochet safety criteria for current and future advanced weapon tests by AD are inadequate. Although no measured ricochet impact points were available, many of the ricochet angles observed on the films were highly conducive to long range travel. Of particular interest were near-optimal ricochet angles resulting after low delivery angle

impacts on revetments. Since the trend in weapon development is continuously toward lower level deliveries at higher speeds, it must be concluded that the current ricochet safety criteria will become increasingly inadequate in the future. For one of the ricochets recorded on film, test team members estimated that the warhead landed approximately 9000 feet downrange after the ricochet, well beyond the usual 6000 feet buffer zone, and a further indication of the inadequacy of current criteria.

3) With a minimum of algorithm development and minor modifications to the programs, existing ricochet models which are hosted on the AD Cyber 176 computer, are capable of generating ricochet safety containment areas for advanced weapons. These containment areas can be used by range safety officers to generate sets of ricochet safety criteria that will adequately insure range safety on tests which have a high probability of ricochet.

2.2 Recommendations

It is recommended that:

1) The proposed modified range planning methodology described in Section 6 of this report should be implemented and utilized for the generation of

ricochet safety criteria on AD tests which have a high probability of ricochet.

2) SEU should include recommended ricochet criteria in an SE OI. In this way, the recommended criteria would be identified as a standard requirement to be used by all range safety officers.

3.0 CURRENT AD RICOCHET CRITERIA AND METHODOLOGY

To determine the existing AD range safety ricochet criteria, a thorough review was conducted of all pertinent range regulations and manuals. Additionally, range safety personnel were interviewed in order to obtain any written or unwritten ricochet information which they might possess. This data search effort revealed that there exists a total lack of guidance pertaining to the areal requirements to contain ricochet impacts.

In the past, concerns for potential ricochet have been alleviated by strict adherence to Air Force regulations and manuals (AFR 50 series and AFM 50-18). These documents provide guidelines for the construction and operation of Air Force ranges. Typically, ranges were made sufficiently large so as to contain the vast majority of weapon impacts and their subsequent ricochets. A prime example of this management practice is evidenced by the vast land resources assigned to the AD range complex.

However, the advent of new weapons and weapon systems has led to a significant increase in ricochet hazard potential. The development process itself adds significantly to the ricochet hazards associated with these new weapons. The operational commands are constantly seeking weapons that have a high probability of kill, while affording aircrews the maximum survivability in their employment. Consequently, weapon developers are continuously designing weapons with higher impact velocities,

more lethal warheads, lower altitude delivery techniques (increasing the probability of ricochet) and increased accuracies and standoff capabilities.

The need to develop and test these newer, sophisticated weapons places additional requirements on the AD range complex. These additional requirements directly affect the potential hazard due to ricochets. The collection of data to document system performance requires that highly accurate and sensitive equipment be located along the projected flight path and in proximity to the intended impact area. Not only is this instrumentation expensive, it sometimes requires that range personnel be present to operate it during the mission. The hazards imposed upon the equipment and the personnel by ricochets are obvious.

Given that a ricochet hazard can exist, the prime concern for the range safety officer is how to adequately determine the hazard area for ricochet due to the employment of a specific weapon. A review of range safety ricochet criteria revealed that the only published data available was taken from a local (AD) publication which has since been superseded (ADTCR 127-4). Data concerning the ricochet associated with guns, cannons and unguided rockets is provided in ADTCR 127-4, but there is a total void of information pertaining to the ricochet of guided and unguided bombs.

ADTCR 127-4 informs the user that: "The ricochet fan will be dependent upon many variables such as bomb weight and shape, impact angle, speed, etc. Thus the ricochet fan must be designed for each mission based upon all known factors which

might contribute to ricochet". However, it does not provide any guidance as to how one might go about designing a ricochet fan. Discussion with range safety personnel revealed that the average range safety officer has a very limited knowledge of the available analytical methods for estimating weapon ricochet. The usual approach is to add an additional buffer zone to the impact area requirements (6000 feet for MK-82/MK-84 inert warheads) to account for any potential ricochet. These ricochet range requirements are basically an outgrowth of the combined experience obtained by the AD range safety officers over a number of years.

This approach to quantifying the ricochet area requirements will probably be more than adequate (but possibly too stringent) in the majority of the missions accomplished at AD. However, there are several instances where the ricochet fan or buffer zone approach would severely limit the range safety officer's options. One example of the inadequacy of this approach is when an item of interest (cinetheodolite camera, tracking radar, range personnel, etc.) falls within a ricochet fan or buffer zone. The range safety officer has a very limited choice of options in this instance. He can:

1) Relocate the target to ensure that the item of interest is clear of the hazard area,
2) Re-orient the attack heading such that the ricochet fan no longer exposes the item of interest,

3) Remove the item of interest from the hazard area (asuming it is mobile),

4) Accept the risk, hope that the worst does not occur and continue the mission (for expendable or low cost items, this could be acceptable),

5) Conduct the mission at another DoD range facility where safety constraints can be satisfied.

Although these options will satisfy range safety considerations, they are often ultra-conservative and confine themselves to situations where range resources are virtually limitless. Of more use to the range safety officer would be a system where the relative hazard to an item of interest could be determined. With this information, missions could be handled on a case by case basis to determine whether or not the potential risk is acceptable. If acceptable, the mission could proceed as planned. If the potential hazard is excessive, minor changes could be made to the mission profile until the level of hazard is decreased to an acceptable level.

As a result of the effort undertaken in this task, it has been found that the current AD ricochet criteria fall within two categories:

1) Ricochet fans applicable for guns, cannons, and rockets are available. These fans are consistent throughout the Air Force, and are based upon the maximum ricochet range analysis conducted by the Calspan Corporation (Reference 1).

2) Ricochet ranges for bombs are a product of the combined experience of the range safety officers. There are no algorithms or methodologies identified to aid the range safety officer in determining when a bomb will ricochet, or to estimate the area required to contain any given ricochet.

Additional examples of the inadequacy of the current AD ricochet criteria and methodology, based upon a review of archived films and data, are presented in Section 5.

4.0 RICOCHET EMPIRICAL MODELS

Ricochet theory was reviewed in depth during a previous study sponsored by SEU (Reference 3). An additional full discussion of the physics of ricochet is beyond the scope of this report. It should be sufficient to point out that an adequate understanding of the physics of ricochet is necessary to assure the proper application of the underlying physical principles in the development of ricochet estimation methodology.

Unfortunately, the equations of motion defining the physics of ricochet do not lend themselves to an easy analytic solution for the purpose of defining ricochet areal requirements. However, due to numerous attempts made during the past 30 years to develop empirical formulas, an alternative approach is available. The empirical approach to predicting the behavior of a ricocheting projectile has been necessitated by the difficulties in obtaining the real world data required in the theoretical formulation of the ricochet process. At best, the ricochet data requirements are poorly defined, costly to acquire, and immense in quantity. Consequently, the most promising results achieved to date have been obtained by treating the ricochet problem statistically.

During the Reference 3 study, computer algorithms based upon References 1, 4, 5, 6, 7, 8 and 9 were developed and used to estimate the initial and ricochet impacts of bombs, 20 mm and 30 mm ammunition, and 2.75 inch rockets. The developed methodology used actual range data to model the initial impact distributions

associated with the various weapons of interest, while the ricochet distributions were generated using an extensive Monte Carlo simulation process. This ricochet model included methods to model the ricochet deflection which has been observed on virtually every instance of recorded ricochet data. This deflection model considered the effects of a non-homogeneous impact media, spin bias associated with spinning projectiles, and deformation of the projectile. While far from an ideal ricochet estimation methodology, this algorithm represents the most comprehensive approach taken to date to bound the ricochet phenomena.

5.0 ARCHIVED RICOCHET DATA AND FILM

One objective of this study was to determine, through the use of archived data and films, whether deficiencies exist in the current AD ricochet safety criteria. Although actual measurements of ricochet parameters (e.g., ricochet velocity and angle versus impact velocity and angle) were found to have been made for several types of objects (e.g., References 6, 7,9), no archived metrical ricochet data for the types of weapons to be tested by AD were found during this study. However, an abundance of information in the form of ricochet events recorded on motion picture film and in the form of informal observations by test personnel were found.

One case which clearly showed that the 6000 feet buffer zone criterion (see Section 3.7) is deficient was that of a ricochet by a Low Level Laser Guided Bomb (LLLGB) using a MK-82 inert warhead. Due to the guidance algorithm employed by the LLLGB, the weapon trajectory was extremely flat during the terminal portion of its flight. Consequently, the weapon ricocheted and was reported to have landed approximately 9000 feet downrange by the test team members (this specific example is archived on film in the SER film file). Had range instrumentation or personnel been located in the ricochet impact area, the potential for a severe safety incident would have been present had only a 6000 feet buffer zone been applied.

Additional film recorded events which appeared to have significant hazard potential included ricochets of the following weapons:

- GBU-15 cruciform wing weapon (CWW) with MK-84 inert warhead. During this test, against a simulated SAM site, it was observed that the revetment appeared to act similarly to a ski jump, resulting in a near-optimal ricochet angle of approximately 45°.
- MK-82 LGB (three cases). In one of these cases, the ricochet angle, after the revetment was pierced, appeared to be near-vertical. Some observers of the film concluded that the ricochet was actually in an uprange direction.
- Maverick
- MK-82 EOGB (HOBO)
- An additional CWW GBU-15

Although the perspective provided by the films of the above ricochet events could easily result in misleading impressions of the ricochet angles, it was estimated that all of the observed angles were greater than 30°. To gain an appreciation for the ricochet trajectory ranges which could result from ricochet conditions similar to those observed in the films, the ricochet impact prediction methodology detailed in Reference 3 was utilized for various ricochet velocities and ballistic coefficients (β). The results are presented in Table 5.1. Since it was assumed that the ricocheting body was flying in a trim, minimum drag condition,

the results must be considered of the "worst case" type. Under these conditions, a 2000 lb MK-84 warhead will normally have a β greater than 1000.

Conclusion

Based upon the review of archived files and data, upon numerous interviews with SEU personnel, upon the exercise of ricochet prediction methodology and upon consideration that the trend in weapon development is continuously toward the designing of weapons to be delivered at lower altitudes with higher impact velocities, it is apparent that the current AD ricochet safety control criteria are inadequate. The archived films show that this is especially true for tests involving impacts at low impact angles against revetments.

Beta	Ricochet Velocity (Feet/Second)	Ricochet Angle (Degrees)	Predicted Ricochet Distance (Feet)
500	1000	40	12957
500	1000	20	10710
500	500	40	5327
500	500	20	3989
1000	1000	40	17894
1000	1000	20	13694
1000	500	40	6240
1000	500	20	4421
2000	1000	40	22445
2000	1000	20	16138
2000	500	40	6856
2000	500	20	4684

Ricochet Distance Predictions

Table 5.1

6.0 PROPOSED RICOCHET SAFETY CRITERIA METHODOLOGY

To identify potential methodologies for generating usable ricochet criteria, it was first necessary to establish a set of evaluation criteria which could be used to determine the effectiveness of any solution. These criteria were formulated in cooperation with SEU personnel:

1) The ricochet criteria should be easily applied to a majority of the AD range missions.
2) Ricochet criteria should not be unnecessarily restrictive and should not adversely affect the planning options of the range safety officer.

With these evaluation criteria available, it was possible to formulate a proposed solution to the AD ricochet criteria problem.

Application of the evaluation criteria to develop an acceptable ricochet criteria led to the following recommended procedure for developing AD ricochet criteria which would not only satisfy range safety requirements, but would also maximize the flexibility of the range safety planner. This recommended approach requires, as a starting point, the use of the ricochet methodology as developed in the Reference 3 study to define the areal requirements for 20mm and 30mm guns, 2.75" rockets and bombs. This methodology is currently hosted on the AD Cyber 176 mainframe computer and is accessible for ricochet criteria development. Since the Range Planning Methodology (RPM) described in

Reference 3 involved the use of a large measured initial impact point data base, modifications to the RPM will be required in order to determine ricochet impact containment areas for advanced weapons to be tested on AD - for which little or no initial impact data currently exists.

It is anticipated that AD/SEU would provide a list of the most common release conditions employed at AD, along with the expected variations about these conditions. The data would, by necessity, be obtained from archived AD/SEU test mission data. This release condition data could then be used to develop an expected initial impact distribution using the DENG computer code (Reference 10). Based on this initial impact distribution, the RPM uses the modified Birkhoff equations coupled with the expected terrain composition and terrain profiles to generate an array of the expected ricochet impact points. This array is statistically modified to provide a ricochet impact probability density function (pdf). This ricochet impact pdf not only defines the area subjected to a ricochet hazard, but also can be used to quantify the expected level of hazard within any portion of the pdf.

Once the ricochet impact pdf's have been obtained, the RPM requires that ricochet impact containment areas be generated for specified containment levels. The ricochet impact containment areas are best defined as closed contour geometric shapes which contain, at a minimum, a specified percentage of the

ricochet impacts. Based on the AD/SEU requirements, ricochet impact containment areas would be developed to describe the ricochet impact hazard area associated with the specific delivery conditions provided. Figure 6.1 contains hypothetical ricochet impact containment areas for 0.995, 0.999 and 0.9999 probabilities of containment. If desired, the containment areas could also be presented as containment fans enclosing the contours shown in Figure 6.1. However, this type of presentation would often be unnecessarily conservative.

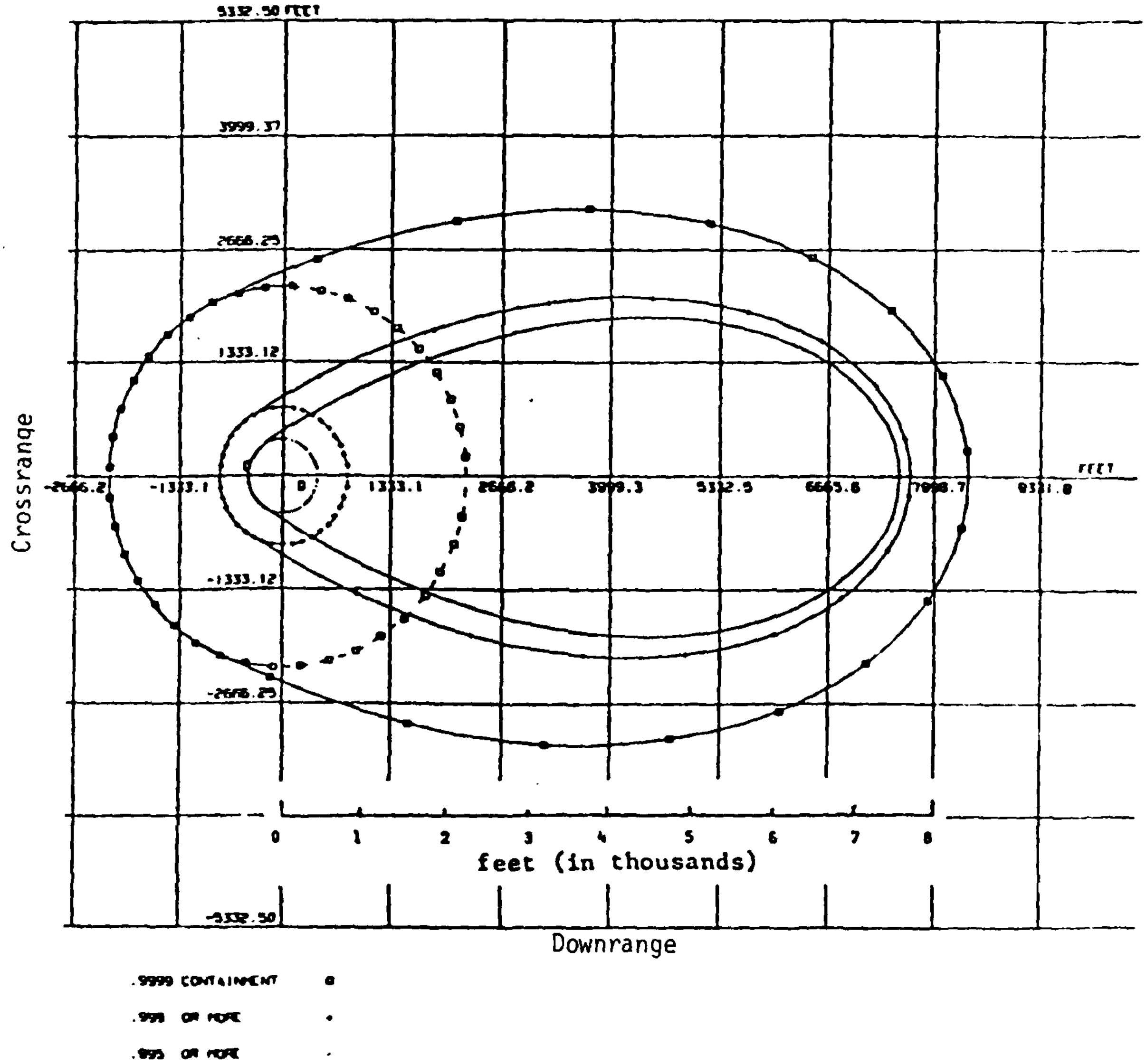
A flow diagram of the computer operations required to generate the ricochet impact containment areas is presented in Figure 6.2. This proposed methodology differs from the RPM methodology of Reference 3 in three major ways:

a) It depends on Monte Carlo sampling of the most common release conditions and their variations to generate the initial impact distribution. The RPM utilized measured impact points.

b) The RPM utilized a closed form large β ballistic impact predictor to generate impact velocities and angles. The proposed methodology will require guided as well as ballistic impacts.

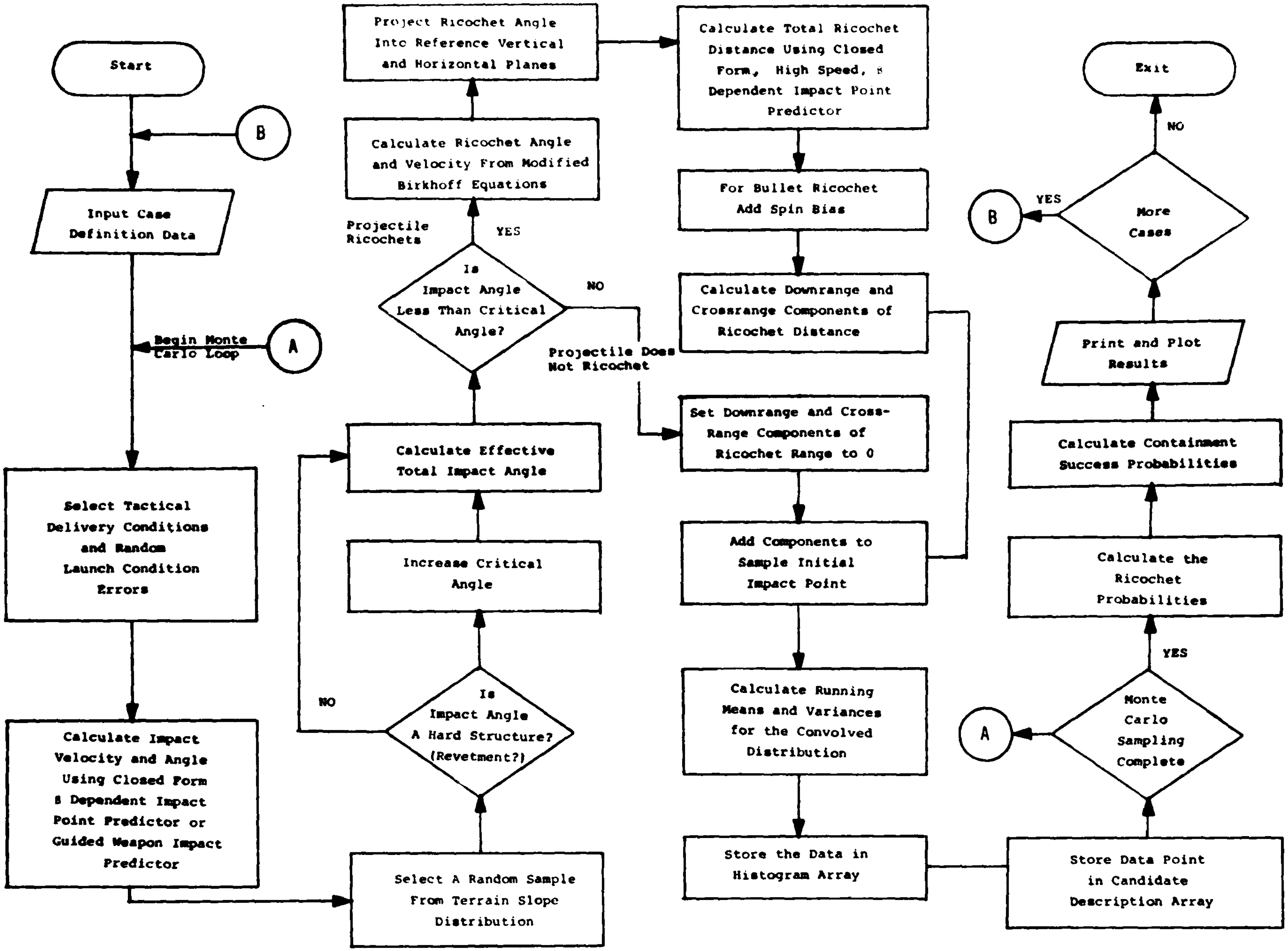
c) Since the initial and ricochet impact data available from advanced new weapons are likely to be minimal, confidence in the generated ricochet impact containment areas must be based largely upon the

accuracy of the assumed delivery parameters. The Reference 3 study avoided this problem to a small degree by basing the ricochet containment contour confidence levels on the statistics of the initial impact data. Because of its reliance upon accurate estimates of uncertainties in the delivery and impact conditions, rather than real ricochet impact point data, the proposed methodology is closely analogous to the GDOP (Geometric Dilution of Precision) methodology used in evaluating the likely uncertainty ellipsoids about trajectory coordinates estimated by range instrumentation.



Hypothetical Ricochet Impact Containment Areas

Figure 6.1



Proposed Ricochet Safety Planning Methodology Flow Diagram
Figure 6.2

7.0 SUMMARY

During this study effort, the status of existing AD ricochet criteria and their validity when applied to future AD test missions were investigated. It was found that the existing ricochet criteria were generally considered to be extremely conservative for most applications. However, a review of archived film data indicated that ricochets can and do often travel substantially further than anticipated. At best, the current AD ricochet criteria are poorly defined and require consolidation for future use.

The existing models for predicting the performance of ricocheting projectiles were reviewed to determine the feasibility of developing a set of ricochet criteria which would increase the flexibility of the range safety planner, while insuring the safety of range instrumentation and personnel. This involved a review of all available documentation of data pertaining to ricochet phenomena.

As a result of the review, a ricochet criteria development methodology was proposed and an existing ricochet model was identified as being both available and suitable, with minor modifications, for the development of AD ricochet criteria.

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STATEMENT OF WORK

AD weapon tests which involve shallow impact angles often result in ricochet. In order to control the safety of personnel and aircraft during such tests, it is essential to know the extent of the space hazarded by the ricocheting weapons and fragments. Impact hazard zones, safe personnel separation distances and safe aircraft altitudes have been developed for some weapons (e.g., GP bombs, 2.75" rockets, 20mm and 30mm rounds). However, the developed safety criteria have often been based upon tenuous physical assumptions and have, in some cases, been made unnecessarily stringent due to a lack of hard data and due to a desire to be conservative for safety reasons. In addition, ricochet safety control for several current and planned weapons (e.g., Maverick, GBU-15, LLLGB, WASP, Hyper-velocity Missile) has been subject to little or no analysis, although it is known that film and data which might be of value in analyzing ricochet hazards related to some of these weapons exists within the archives of AD and other agencies.

An overview and analysis of current AD range safety ricochet hazard criteria and of future requirements is needed in order to ensure that the criteria are reasonable and adequate for ensuring safety on tests involving a high probability of ricochet (and are not unnecessarily test restrictive). The contractor is directed to perform such a task, which will include the following steps:

1) Review all current AD range safety ricochet hazard criteria and methodologies for determining the criteria. Identify any deficiencies in the current criteria and methodologies.

2) Acquire and review all film or other data existing in AD or other archives related to ricochet of weapons to be tested by AD. Identify data which might be used to improve current and future range safety ricochet criteria.

3) Based upon 1) and 2), develop a plan for improving the current range safety ricochet hazard criteria and methodology. Identify algorithms which must be developed in order to provide improved criteria.